Beam-Based Alignment Studies

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- IR Quadrupole BBA
- Transition jump quad BBA
- Electron cooling solenoid BBA

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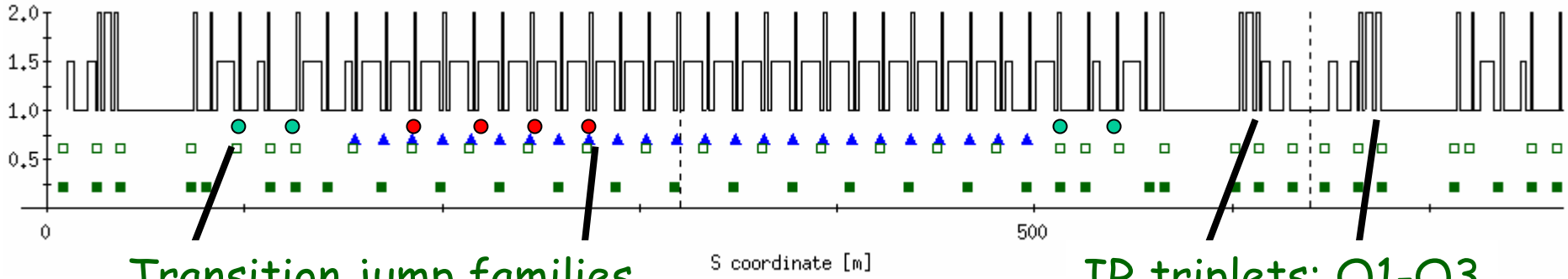
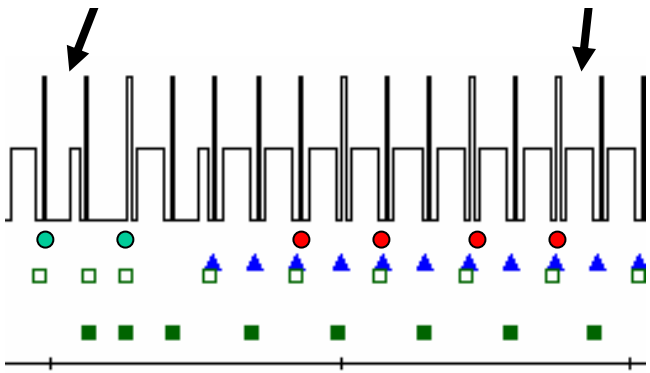
RHIC BPMs and BBA layout

One sixth of one RHIC ring:

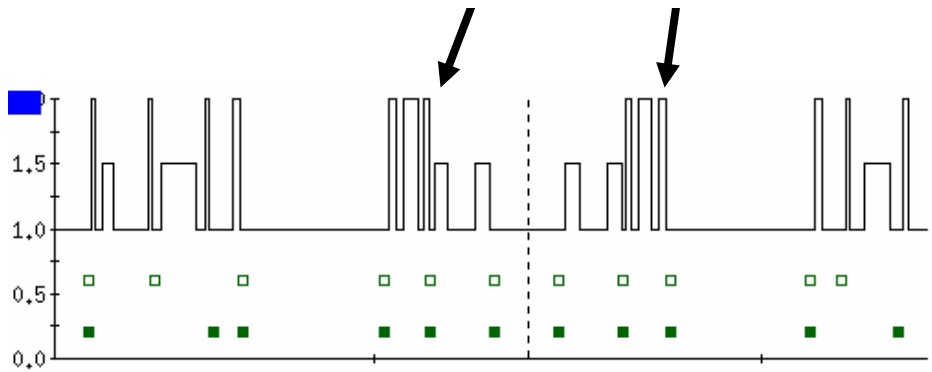
6 IR quadrupoles, 54 BPM planes, 24 chrom sextupoles (2 families), transition jump quadrupoles (2 families)



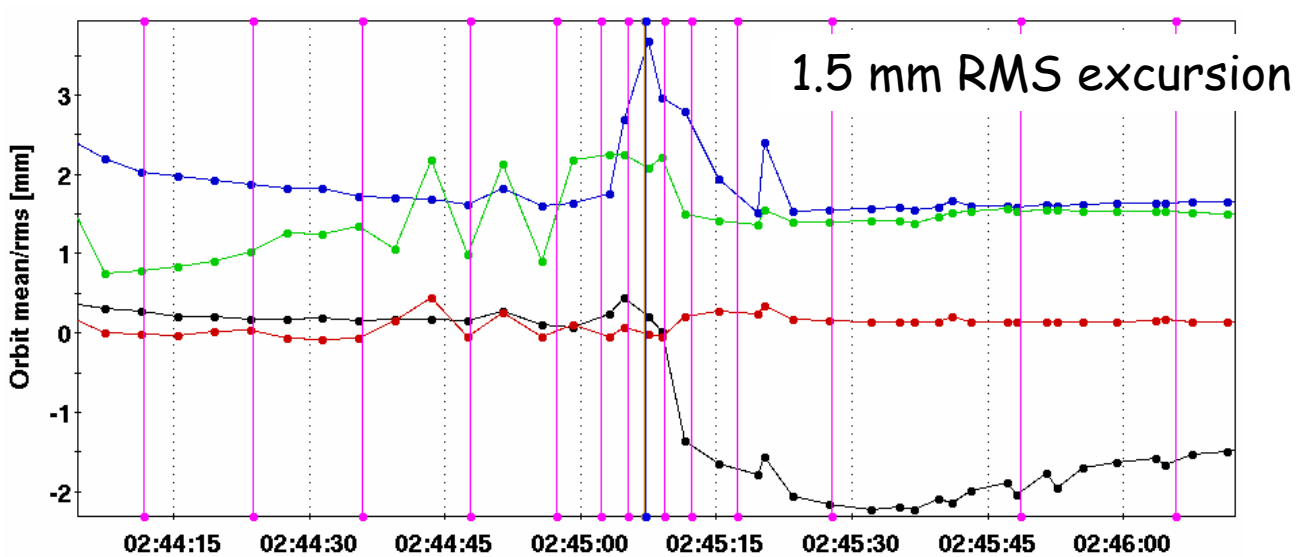
Transition jump families



IR triplets: Q1-Q3



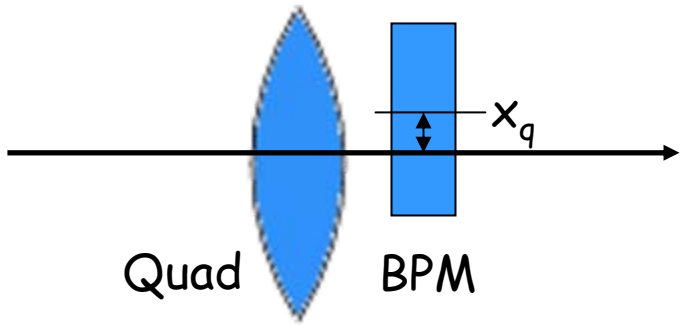
- Why beam-based alignment (BBA) at RHIC?
  - Improve steering through IR quads
  - Maximize aperture through β* squeeze, minimize backgrounds
  - Minimize orbit/lattice disruptions during transition jump



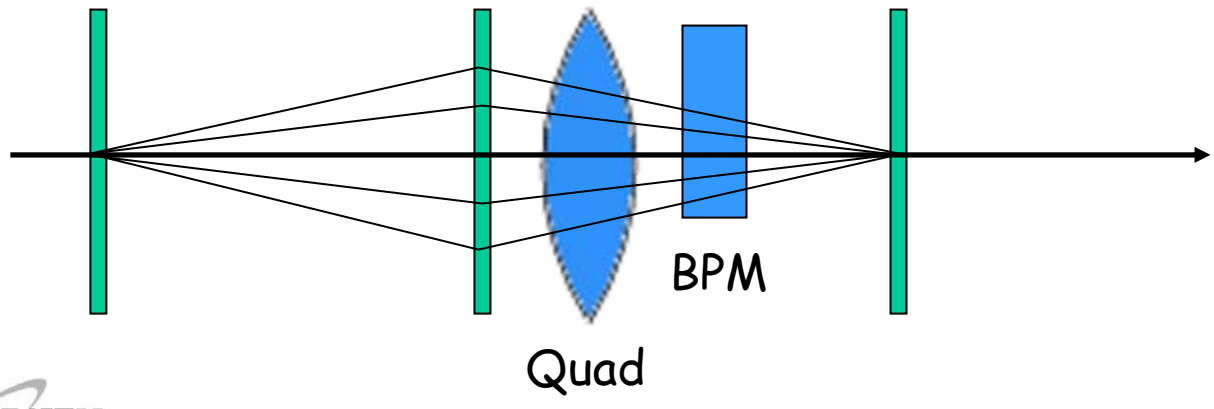
  - Polarization preservation for polarized protons
  - Systematic evaluation of BPM electronic digital offsets

Quadrupole BBA Approach

- Measure beam offset x_q from beam position monitor (BPM) center when steered through nearby quadrupole center



- Vary quad strength and three-bump across quad; minimize dipole kick θ from quad as function of BPM reading (slow!)



- Changing quadrupole of strength k by Δk produces a feed-down kick of θ, the offset is given by

(1)
$$x_q = \frac{\theta}{\Delta k}\left(1 + \frac{k\beta}{2\tan(\pi Q)}\right)$$

  - This includes the effect of changing closed orbit at the quadrupole; it diverges near integer tunes, and the second term is negligible near half-integer tunes.
  - For RHIC pp operations, Q=0.72-0.73. For RHIC heavy ion operations, Q=0.23-0.24. In both cases, $\tan(\pi Q) \approx 1$.

  - Additional dispersive term is required if dispersion at quadrupole is large; RHIC pp operation is "close" to transition

Thin-lens correction and IR quad parameters

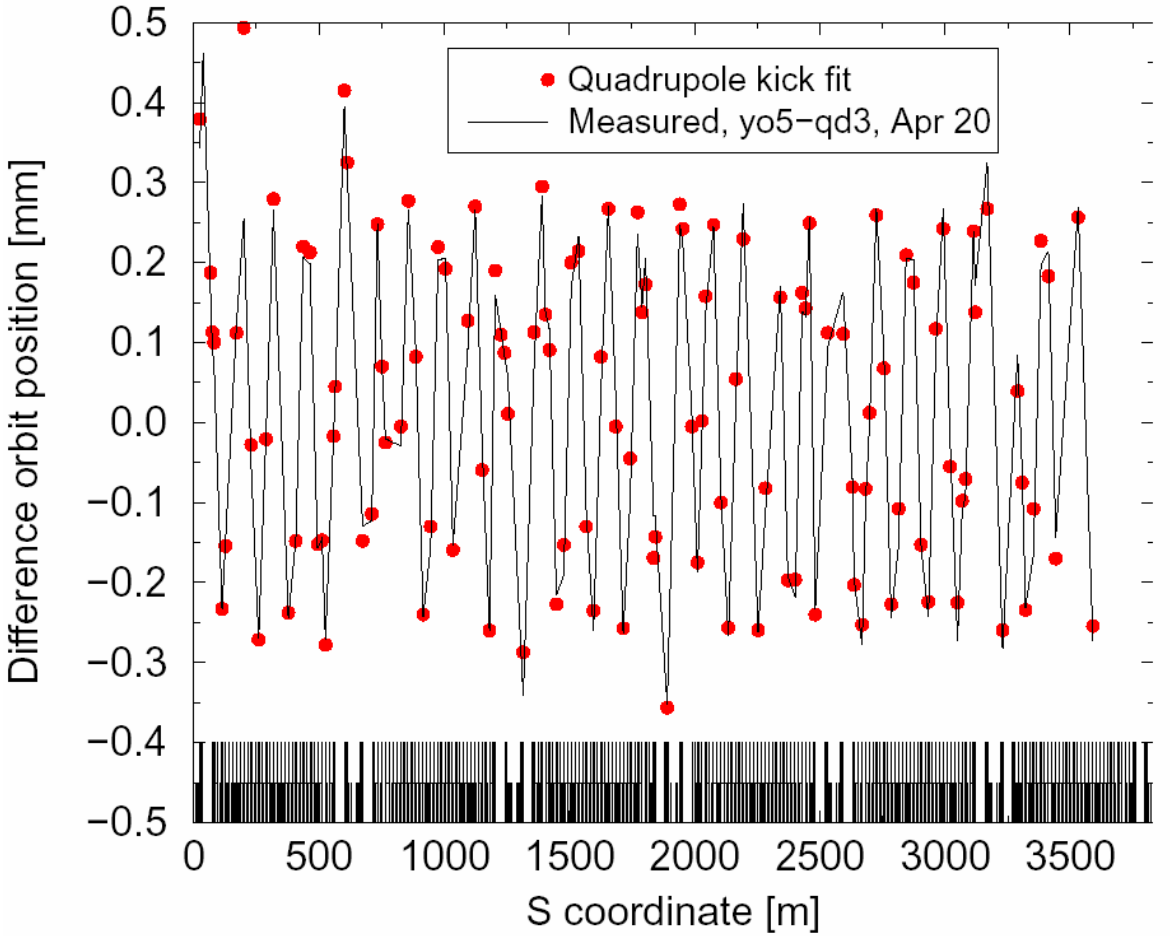
- Hoffstaetter/Willeke [PRST:AB 5, 102801 (2002)] found the scaling error in thin-lens approximation for IR quadrupoles:

$$\sigma^{-} = \frac{l\sqrt{k} - \sin(l\sqrt{k})}{2l\sqrt{k}}$$

Name	Length [m]	Strength k [m^{-2}]	β_x [m]	β_y [m]	Scaling error σ^{-}
bi5-qf3	3.39	0.1148	114.47	62.06	0.103 (!)
bi5-qf1	1.44	0.0809	76.10	82.83	0.014
bo6-qd1	1.44	-0.0809	83.00	78.36	0.014
bo6-qd3	3.39	-0.1148	61.87	148.49	0.103 (!)
bo11-qd1	1.44	-0.0809	80.91	76.45	0.014
bi12-qf1	1.44	0.0809	76.95	80.95	0.014

- Typical RHIC IR quadrupole parameters in β^*=10m injection optics
  - Red BPMs names have unmodified BPM electronics boards

Quad BBA results: typical quadrupole fit



- Single-parameter fit using online model optics functions with quadrupole change
- $\Delta k = 6 \times 10^{-3}$ m^{-2} ($\Delta k/k \approx 5$-7%)
- Measured difference orbit RMS 100-300 μm
- Residual difference orbit RMS is 5-15 μm (5%)

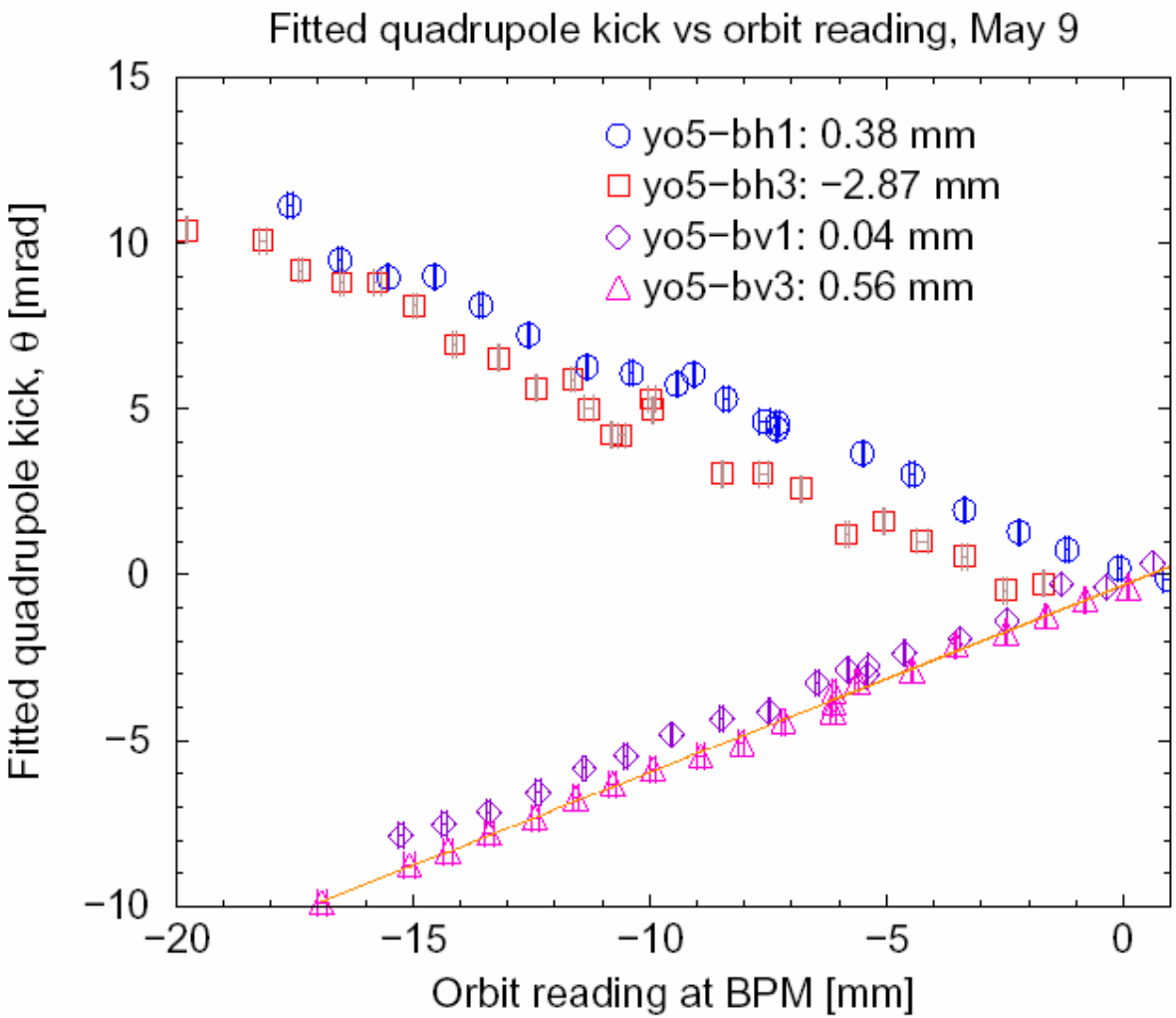
Quad BBA results: BPM board comparison

- Modified BPM boards (with relays removed) have o(10) more consistent offsets than boards with original relays
- Accumulated BBA data acquired over 2 months of Cu-Cu, pp operations, includes short- and long-term drift
- Some recalibrations occurred early in study

Name	Horizontal [mm]	Vertical [mm]
bi5-qf3	-1.07 ± 0.16	-0.24 ± 0.00
bi5-qf1	-1.78 ± 0.34	0.08 ± 0.13
bo6-qd1	0.28 ± 0.06	-1.46 ± 0.62
bo6-qd3	-0.33 ± 0.19	-2.59 ± 0.23
bo11-qd1	-0.39 ± 1.62	1.31 ± 1.10
bi12-qf1	-0.87 ± 1.59	2.84 ± 2.85
yo5-qd3	-2.87 ± 0.15	0.56 ± 0.25
yo5-qd1	-0.38 ± 0.22	0.04 ± 0.14
yi6-qf1	-0.56 ± 0.47	-0.03 ± 0.27
yi6-qf3	-1.41 ± 0.40	-0.16 ± 0.18
yi11-qf1	-8.31 ± 1.32	-0.48 ± 0.26
yo12-qd1	-0.38 ± 1.85	1.88 ± 1.50

Red BPM names have unmodified electronics boards

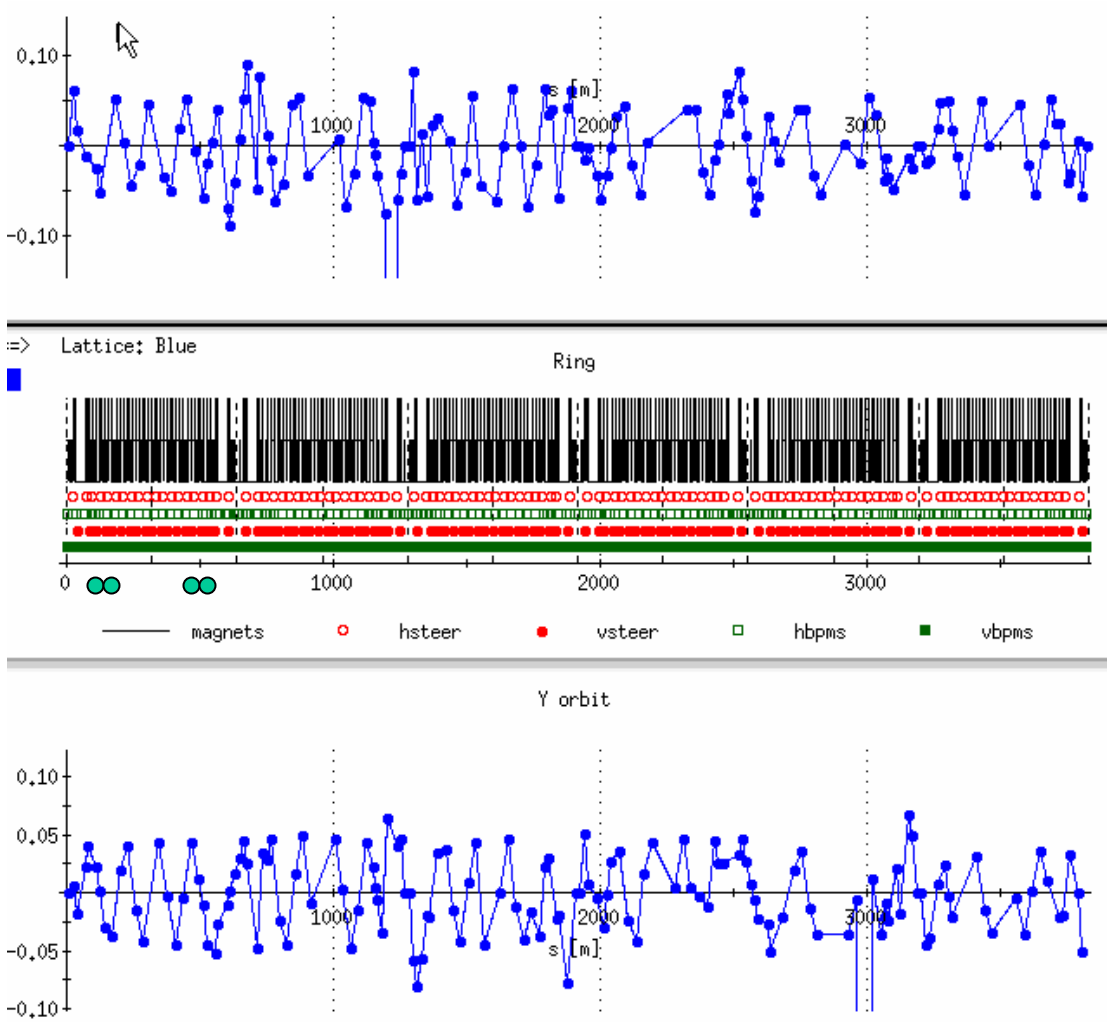
Quad BBA detailed scans/comparison



- Detailed bump scans (25 points) performed to compare against cursory scans with three points
- Agreement is within statistical error bars
- Orbit bumps biased to negative by RHIC injection IR separation bumps

Transition jump quadrupole BBA

- Each transition jump family has four quadrupoles.
  - One family dispersive
  - One family nondispersive
- Extra dispersive terms in (1) included. Four-parameter fit for kicks
- Varied family strengths by $\pm 3\text{-}5 \times 10^{-3}$ m^{-2}



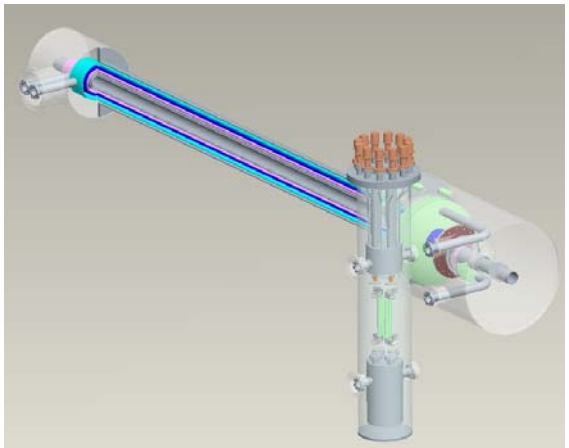
Transition jump quadrupole BBA results

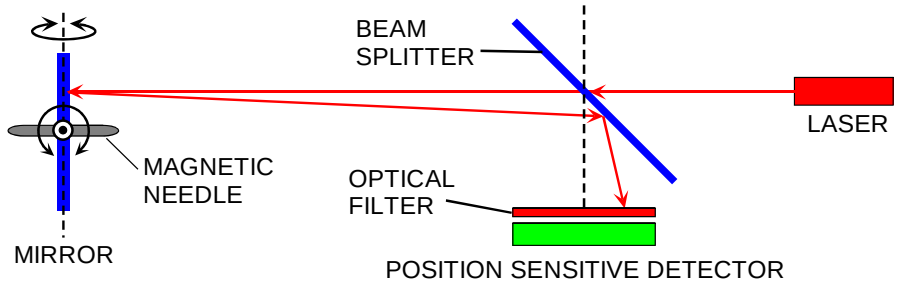
Name	Horizontal [mm]	Vertical [mm]
bo6-b12	-2.00	1.76
bo6-b14	-2.21	1.45
bo6-b16	3.45	-1.24
bo6-b18	-16.32 (!)	0.34
bo6-b6	-2.60	-2.47
bo6-b8	1.84	-0.10
bo7-b8	-0.42	6.42
bo7-b6	-3.33	5.27

Blue values are from intentional +5mm bumps

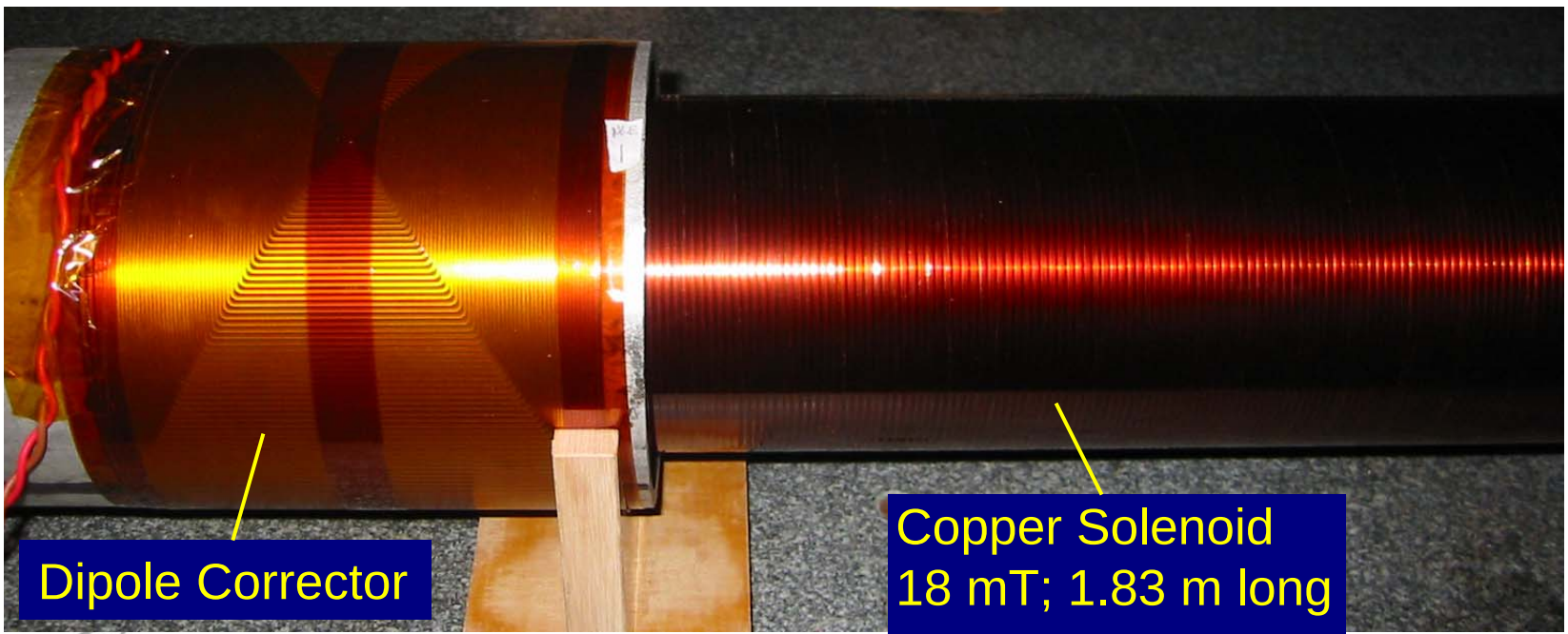
- Very low statistics (one study, five family settings per family)
- 78 degrees/cell phase advance
- Fit is within a few mm, typical for no bumps and single-pass fit of dispersive form of (1)
- Individual 3-bumps across each individual quadrupole will isolate individual quadrupole responses

Electron cooling solenoid R&D: <10 ppm Uniformity

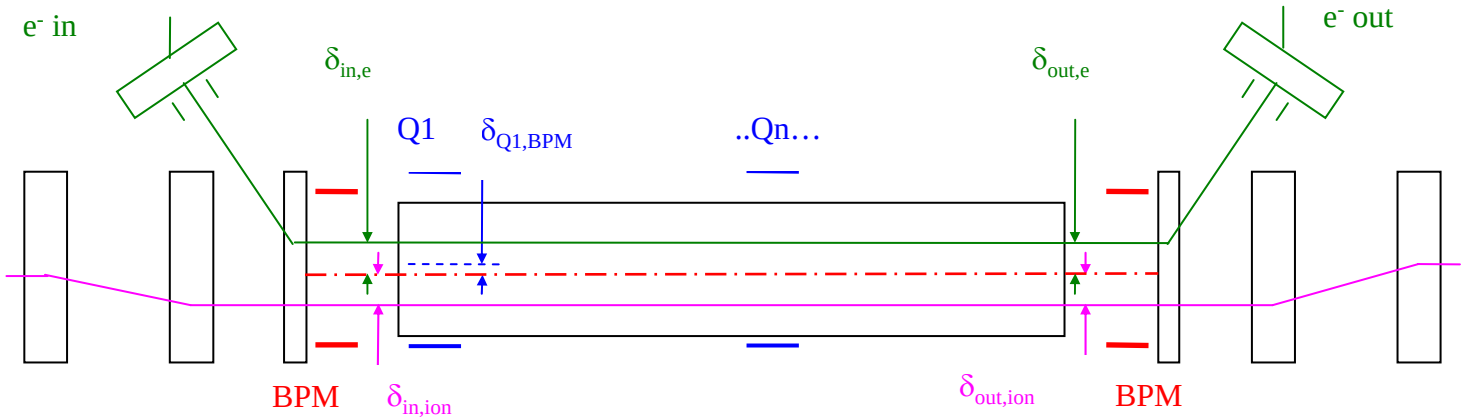




2x13m, 5 T solenoid design started

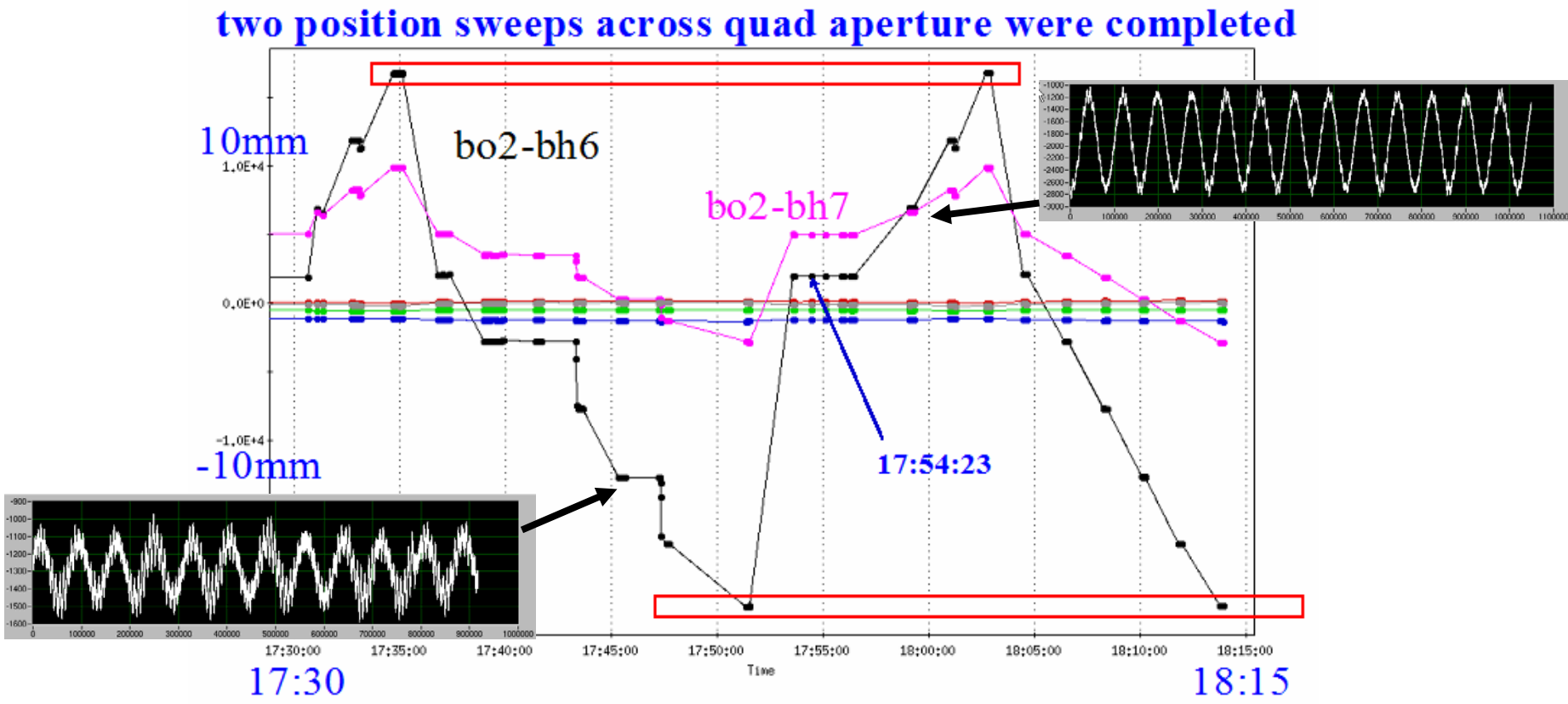


Electron cooling solenoid BBA technique



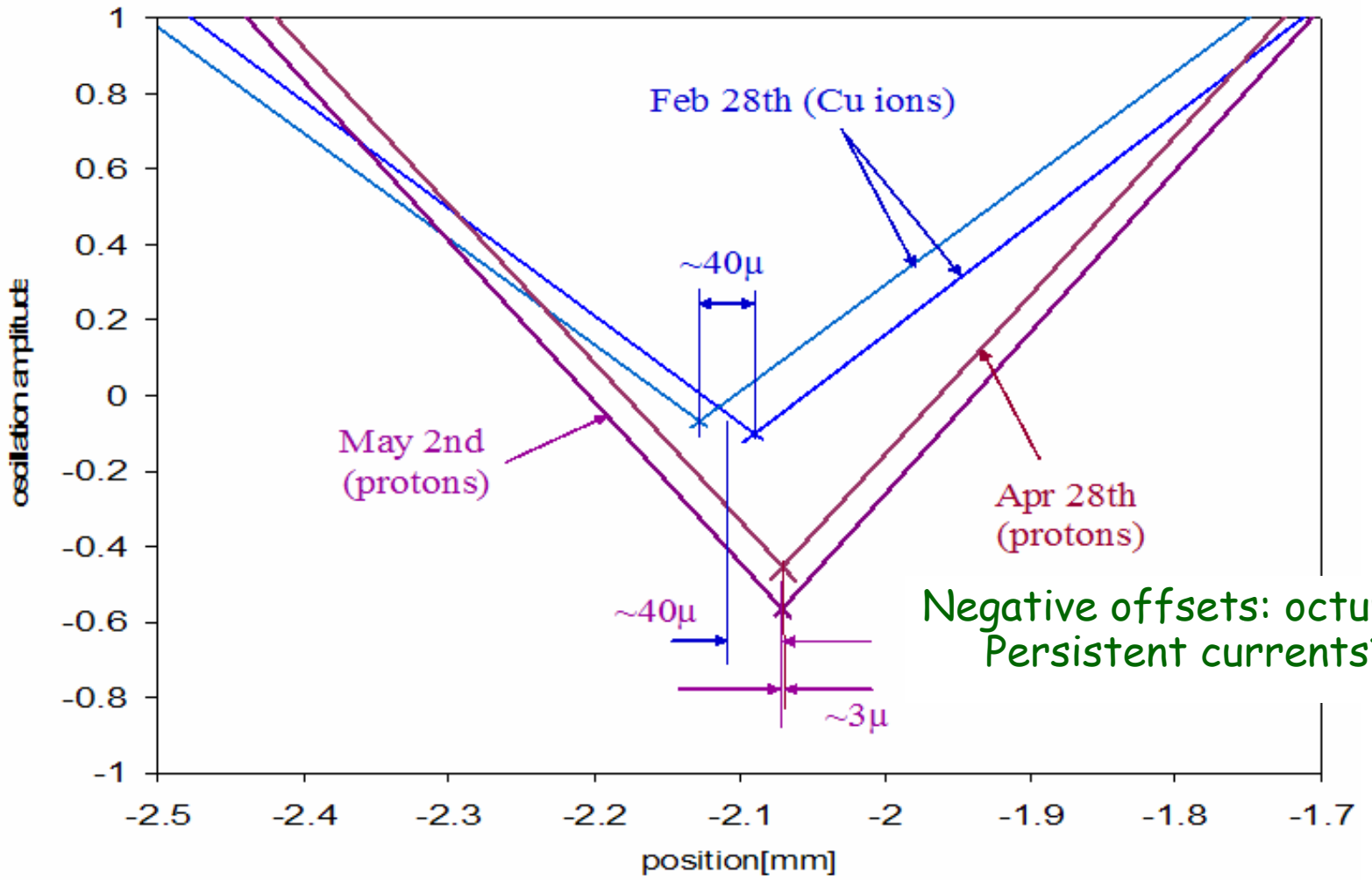
- Individual quadrupole coils in the 13m solenoid are modulated at 1-10 Hz.
- Minimize orbit response outside solenoid at this frequency to center ion beam in quadrupole coils, fiducializing with respect to alignment BPMs. Align ion beam.
  - Requirement ⇨ 10 μm reproducibility
- Use local electron beam three-bumps within the solenoid to iteratively align the electron beam to the ion beam.

Electron cooling BBA ion beam alignment



- Move beam position, modulate quadrupole at 1 Hz and measure million-turn BPM response at 1 Hz

Electron cooling BBA results



Negative offsets: octupole?
Persistent currents?

RHIC BPM/BBA plans and improvements

- Improve quality of RHIC BPM measurement reproducibility
  - Relay removal, improved calibrations, eliminate systematics
  - Average orbit data should reproduce to 5-10 um (but 10 Hz…)
- Initial IR quadrupole beam-based alignment successful
  - Reproducible measurements to 100-200 um
  - Calibration drifts and recalibration still need to be studied
  - Slow measurements improvable with multiple modulations
- Transition quadrupoles
  - Requires more statistics in next HI run, including local bumps
- Electron cooling solenoid BBA
  - Requires 10 um alignment reproducibility
  - 40-50 um accuracy, octupole systematics require small steps